UAV Autonomous Operations for Airborne Science Missions

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Autonomous UAV science missions hold great promise for improving the productivity of airborne science research and applications. Potential UAV science missions have been reviewed and common autonomy needs have been identified. Preliminary efforts to craft an Intelligent Mission Management architecture for observational autonomy are evolving. Three science missions, along with the architecture, the technology needs and operational requirements for autonomy are highlighted.

Nomenclature and Acronyms

CDE	Collaborative Decision Environment
CIP	Collaborative Information Portal
FL	Flight Level
GA-ASI	General Atomics – Aeronautical Systems, Inc.
HALE	High Altitude Long Endurance
LASE	Low Altitude Short Endurance
MODIS	Moderate Resolution Imaging Spectroradiometer
NAS	National Airspace
NASA	National Aeronautics & Space Administration
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take Off & Landing

I. Introduction

Within NASA, the Earth Science Enterprise has long sought to use Unmanned Aerial Vehicles (UAVs) for science and application missions to complement other measurement platforms, including manned aircraft and

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satellites. UAVs are able to collect science data that is hard to gather using other available platforms. These include high altitude atmospheric composition measurements and earth surface events in inaccessible places over extended periods of time. UAVs are capable of providing unique data gathering opportunities as a result of their operational characteristics. However, UAVs currently require monitoring by ground-based operators, which adds expense. Further, they are limited in their operational scope by delays and blackouts in communication. When the aircraft and its payload are provided with autonomous functionality, even greater science and application productivity is promised. These platforms are destined to become part of NASA's Sensorweb — a networked set of instruments in which information from one sensor is automatically used to redirect or reconfigure other components of the web.[1]

A new project within NASA is seeking to understand and develop autonomous capability for the entire UAV system, including the aircraft, the payload, the communications system and the ground station. Preliminary efforts to craft an autonomous "Intelligent Mission Management" architecture were begun in early 2004. Concepts of Operation and Functional Design Requirements for atmospheric sensing and wildfire monitoring missions have been developed as a first class of missions to drive the development of technologies that will enable highly autonomous operation.

II. UAV Characteristics

UAVs are of particular interest for airborne science because of unique features that enable missions not possible before. Some of the advantages of UAVs are listed below. Compared to manned aircraft:

- UAVs can be flown in dangerous situations, because there is no pilot or scientist on board. For example, UAVs can be flown through toxic plumes for in situ sampling.
- UAVs can fly long duration, dull missions, such as mapping or for diurnal measurements, without inconveniencing pilot or crew.
- UAVs with long endurance can loiter during an emergency, enabling long-term situational awareness.
- UAVs with long range capability can be launched from a remote location, or flown to a remote location.
- UAVs with high altitude capability can fly safely over weather and above air traffic.

Compared to satellites:

- UAVs can fly to precisely selected locations at precisely selected times.
- UAVs can be tasked to loiter over arbitrary targets for long durations.
- UAVs can carry a variety of interchangeable high resolution imaging instruments.
- UAVs are recoverable for maintenance and upgrades of sensor and communication systems.

In summary, UAVs can provide more temporal and geographic flexibility than satellites with fewer human risks and costs than manned aircraft systems.

A variety of UAVs are available or in experimental development at this time. They range in size and payload capability from very small (carrying 5 lbs) to extremely large (carrying several thousand pounds). They also range in altitude capability from several hundred feet to over 65,000 feet. Available UAV systems have varying capability for control through line-of-sight or over-the-horizon via satellite link. The data management systems also range from simple to sophisticated. Finally, the environmental conditions in which the payload instruments must operate also vary. Each has unique features and potential for science missions. Some currently flying UAVs and their characteristics are shown in Table 1.

For UAVs to become routinely available for science missions, they must demonstrate suitable performance, reliability, and become accepted in the National Airspace (NAS). Achieving the desired flexibility, and thus science productivity, while reducing human risks and costs can be achieved by increasing the levels of autonomy in the overall system. This project has focused on these autonomy issues. (A parallel effort to gain routine access to the NAS is the ACCESS 5 program, managed from NASA's Dryden Flight Research Center.[2])

For early development of intelligent mission management, the project team has been using the Altair UAV manufactured by General Atomics - Aeronautical Systems Inc. (GA-ASI) as a representative high altitude platform, and a Yamaha RMAX helicopter as a low-altitude platform. These two aircraft are shown in Figures 1 and 2.

Table 1. Capabilities of UAV Platforms

	Manufacturer / Operator	Maximum Altitude, ft	Endurance, hrs	Payload Wt., lb
Big Birds (large payload)				
Altair	GA-ASI	55,000	24	700
Predator B	GA-ASI	52,000	20	650
Global Hawk	Northrup Grumman	65,000	36	1900
High Altitude (moderate payload)				
Altus DT	GA-ASI	60,000	6	150
Altus ST	GA-ASI / CIRPAS	45,000	30	150
Perseus B	Aurora	60,000	6	110
Low Altitude (moderate payload)				
RPV-3	Lockheed Martin	10,000	6	22
Scorpion	Freewing / Scaled	15,000	4	57
Solar				
Pathfinder Plus	Aerovironment	70,000	14	50
Small, low altitude				
Mark 3	Aerosonde	13,000	36	5
Scan Eagle	Boeing / In Situ	16,000	15	camera installed
Pointer	Aerovironment	1,000	0.3	2
VTOL				
RMAX	Yahmaha	10,000	1.25	35

Figure 1. General Atomics Altair UAV

Figure 2. Yamaha RMAX UAV

III. Autonomous Operation

UAVs obviously have no pilot on board, but are often flown by pilots on the ground who monitor and command the aircraft through remote control. Although this type of operation may be acceptable for short duration flights where the pilot has adequate information from on-board sensors to make real-time decisions, it is a goal of this and other projects to relieve the pilot of most aspects of decision-making by automating as many flight and data-gathering processes as possible. The advantages of autonomous operation include: reduced personnel requirements and costs, consistent decision-making based on pre-programmed rules, and greater scientific productivity due to flexible, optimized, intelligent flight and payload operations. This project is being undertaken by the Vehicle Systems Program of NASA's Aeronautics Research Mission Directorate.

A. Autonomy Architectures

The UAV autonomy architecture is adapted from remote agent architectures commonly used for other NASA applications (e.g. the Deep Space 1 Remote Agent).[3] Such agents are designed using a “sense-think-act” closed loop control paradigm. Agents sense their environment and determine what “state” they are in; this includes both external factors such as location and altitude, as well as internal factors such as state of communications, fuel load, and the state of repair of critical components. Agents may receive new goals from their operators, state updates from other UAVs, or commands to perform new actions from the operator. Agents then think about the goals they have been asked to achieve (e.g. locate a fire near an approximate location) and determine how to accomplish these goals. At times, the agent may have a plan of action ready, but at other times (e.g. after being asked to accomplish a new goal or given an override command) they may need a new plan. In order to handle uncertainty about either the state of the world or the results of their actions, agents may build several plans with contingencies. Agents then perform actions in order to execute the plan. The next step is to wait for feedback from those actions to determine the next state, at which time the loop begins again.

The task of instantiating this architecture for a UAV requires dividing functionality between the payload, the vehicle, the ground station, and the human operators. As one example, a UAV may have enough processing power onboard to develop long-range plans to achieve general goals, but may not be able to analyze sensor data. In this case, sensor data is sent to the ground station for resource-intensive processing and analysis by the operator. As another example, UAVs with little on-board processing power may not be able to perform many autonomy functions on their own. In this case, long-range planning must be performed at the ground station, with humans taking on the most general and abstract decision-making tasks. Much of the autonomy architecture is common across sensors, UAVs and missions, and can therefore be reused for different UAV systems. The architecture for the system is shown in Figure 3.

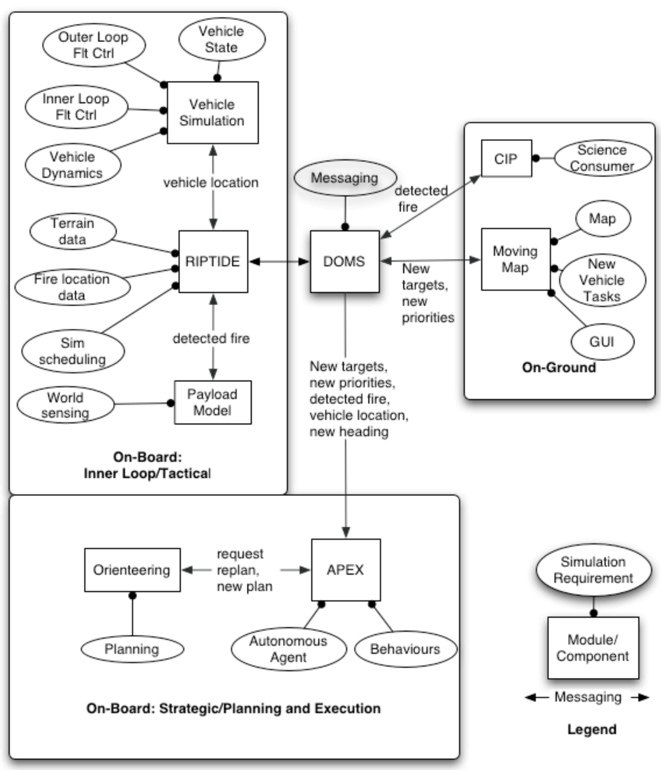

Figure 3. Autonomous Architecture for UAV Flight with Re-tasking from Payload or External Inputs

B. UAV Autonomy Capabilities

A UAV becomes more autonomous as more and more decision-making functionality is transferred from the human operator to the UAV system. Taking advantage of the unique capabilities of UAVs requires autonomy functionality in both the aircraft and in the payload. For example, even though the aircraft may nominally be flown from a ground station by a pilot, it could be programmed to follow pre-determined waypoints. The payload instruments must also operate without hands-on control, either through remote control or built-in functionality. Introducing autonomy also requires special risk-mitigation strategies. To ensure safety, the aircraft must be programmed to follow some course of action if communication is lost with the pilot on the ground. Beyond these minimal requirements, autonomous operations can improve the productivity of a mission, for example by allowing dynamic replanning of the flight path.

Various autonomy capabilities are being developed for UAVs, including:

- Aircraft health system monitoring, including fuel level, state of communications link, and payload health.
- On-board payload information processing to reduce data or direct UAV operations.
- Flying a pre-programmed flight profile, including lat/long, altitude, time on station.
- Goal-directed, tactical flight profile based on real-time on-board sensor information (e.g. payload-in-the-loop).
- Automated, strategic revising plan based on input from scientists or pilot on the ground.
- Automated coordination of multiple UAV operations, e.g. mother-daughter ship operations or formation flying.

C. Collaborative Decision Environment

The Collaborative Decision Environment (CDE) is a ground system intended to enhance the situational awareness and decision-making process among team members during long endurance science missions. It consists of integrated data management, mission planning and scheduling, and decision support tools in a secure collaborative environment. The CDE provides personnel participating in the UAV mission with an interface to the payload systems, and to any external data sets, personnel, or sources of information necessary for the accomplishment of that mission. The CDE affords the means to visualize, observe and interpret data obtained by the payload; to visualize, observe and interpret mission-related data from sources external to the UAV system; to monitor vehicle and sensor health status; to direct the payload systems (and indirectly the UAV); to communicate with other team members; and to integrate sensing goals into autonomous mission planning. Some of these capabilities, such as managing heterogeneous data, viewing personnel and event schedules, and broadcasting messages were first developed and deployed in a system called the "Collaborative Information Portal (CIP)" for the recent Mars rover missions as described in Ref. 4. A design requirement is to implement standardized interfaces for communicating between sensors, ground system, and the UAV autonomy architecture in order to provide for future missions in which multiple payloads on a single UAV or multiple UAVs interact to form a distributed sensor. Since the CDE is a distributed system intended to support remote users interacting with sensors aboard the UAV, secure protocols are required to prevent unauthorized access.

IV. Earth Science Missions

In this paper, the missions that drive autonomous design features are determined by the needs of the Earth scientist. Input to the project from this community is significant; both the fundamental science and the applied science areas are considered. The impact on science from using autonomous UAVs as measurement tools can be very significant and the topics are broad. For this project, several representative UAV Earth Science missions have been considered in detail by mission scientists and sensor designers in order to examine ideal levels of autonomy. The concept of operations for these missions has led, in turn, to functional requirements, which are now being addressed by researchers in the robotics and information technologies areas. Three missions are presented to illustrate the phases of operation, with emphasis on those activities, which either require or would be greatly enhanced by autonomous operation. Each mission makes use of an integrated payload/platform system to automatically respond to mission parameters as well as aircraft status and environmental conditions. The first mission is a high-altitude atmospheric composition mission to measure, via *in situ* sampling, specific chemical or physical conditions that contribute to climate change. A mission in which the instrument measurements guide the flight path requires real-time analysis and a high degree of autonomy. The second is a high altitude mission to detect and monitor wildfires. The goal in the high altitude fire mission is to detect wildfires and communicate location and imagery to fire crews on the ground. Here the sensor system must be automated to search for fires at designated positions, revise plans when fire detection takes longer than anticipated, track satellite passes to ensure transmission of data, and monitor fuel state to ensure safe return of the vehicle. The third is a mission to more closely map fire fronts using a low altitude, terrain-following vertical take-off and landing (VTOL) UAV. In the third mission, the VTOL UAV is guided by proximity to the fire front in real time, requiring a suitable degree of automation.

A. High-altitude Atmospheric Composition Measurements

Scientific questions related to global climate change center around the changing composition of the atmosphere. Answering these questions requires data at altitudes ranging from the Earth's surface to the stratosphere and at all latitudes from the poles to the equator. Whereas NASA scientists have been able to gather valuable insights from measurements taken from the ER-2 and other platforms, these measurement tools are not ideal for obtaining a complete data set. A comprehensive set of measurements requires ease of reaching all latitudes, greater duration at altitude, and the ability to fly vertical profiles. In addition, real-time analysis of the *in-situ* atmosphere composition would allow greater measurement productivity. This capability would allow real-time redirection of the flight path to the locations of greatest interest. Today it is possible to imagine a scenario in which scientists on the ground redirect the sampling probe (UAV with instruments) in geographic coordinates or to carry out a vertical scan. In the future, it might be more ideal for intelligent systems incorporated in the payload to redirect the platform to follow composition profiles.

In another typical mission, scientists might investigate the tropical cirrus cloud physical properties and formation processes for successful modeling of the Earth's climate. Representative steps in such a mission would be to track a vortex from a satellite, identify a filament target, monitor trace gas maximums to guide the flight trajectory, and then monitor filament evolution over multiple diurnal cycles. Horizontal surveys (thousand of miles) with vertical profiles (0 –30 km) might be needed to determine (chemical and thermodynamic) structure. The science team, or the intelligent mission manager, might then revise the flight plan to investigate emerging targets of interest (aerosol loading in clouds, mountain waves promoting stratospheric mixing), or to monitor atmospheric profiles with a limb sounder at constant sun angle. The mission might also call for an investigation of structures in fine detail with expendable probes (dispensed from a mother-ship). A fully integrated system would guide observations of atmosphere based on changing in-situ and/or satellite data. The aircraft system must also be able to avoid threatening weather and traffic. Finally the aircraft would return safely when the mission is complete.

A profile for a flight following a Lagrangian in atmospheric conditions is shown schematically in Figure 4.

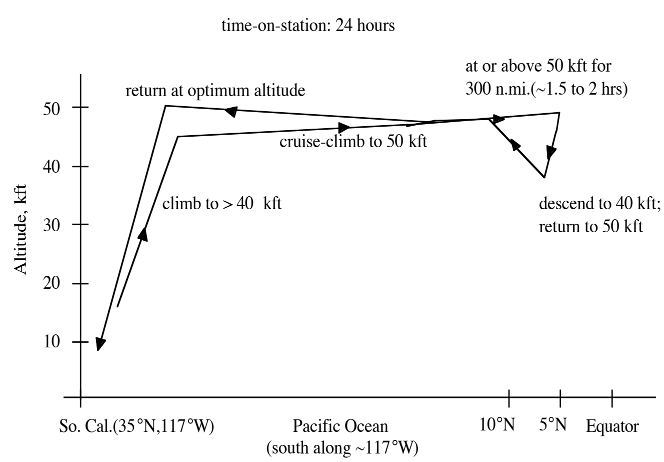

Figure 4. Flight Profile for Atmospheric Sampling Mission

B. High-Altitude Disaster Monitoring with Wildfire as an Example

UAVs with long duration loitering capability are ideal for monitoring hazardous or disastrous events on Earth's surface. These could be natural events such as hurricanes, floods, volcanic eruptions or wildfires. They could also be man-made events such as toxic releases, traffic problems or terrorist activities. The common characteristics of the data gathering are the need to reach the event location, the ability to loiter more or less in place over the event (but out of the way), and the capability to receive and send data to other locations. UAVs have been proposed for wildfire observation because they meet these needs.

One important aspect of a wildfire observation mission is the ability to send images to fire commanders on the ground in near-real time. Another is the ability to move to other locations, as multiple fires usually occur during fire season. A UAV could be directed from the ground to change locations, or pre-programmed to scan selected coordinates to search for fires and then loiter if fire is detected, or directed by satellite observations such as the MODIS fire mapper.

In a representative mission, a long-duration autonomous UAV would be deployed to monitor the western US, to identify or verify new wildland fires based on satellite observations, to report fire status, to request additional observational support, and/or to predict fire behavior. A joint effort between NASA and the US Forest Service to demonstrate fire monitoring in the Western US is described in more detail in Ref. 5.

In a typical mission, the science team would track air to ground lightning strikes from satellite to identify potential fire targets, prioritize potential targets based on risk to people and property, guide flight trajectory, and investigate and report fires, possibly over multiple diurnal cycles. An operational system would revisit as needed. A full survey might require horizontal scans (FL250)(thousand of miles) with vertical profiles (to 5000 AGL) to monitor at fine resolution. Expendable probes or a call to a low-altitude aircraft could also be used to obtain more detailed information, as discussed in the next section. A fully automated system might even be expected to manage the flight plan to optimize the acquisition of cloud-free images. Alternatively, the instrumentation package might be designed to manage fire observations to establish perimeter or fire temperature, to provide real time imagery to fire fighters, or communicate fire perimeter to local Incident Commander. A loitering aircraft could provide a communications net to fire fighters as needed. The UAV might be expected to revise the flight plan to investigate emerging targets of interest, based on satellite input, onboard sensors, or public spotters. Another possibility would be to provide guidance for unmanned fire suppression aircraft to extinguish the fire, as this is one of the most dangerous missions for pilots. For post-fire restoration efforts, an imaging system could map the fire's extent and assess the condition of the burned area. In all cases the UAV flight system would be designed to avoid threatening weather, terrain and traffic. The aircraft would return safely when the mission is complete.

The flight profile and flight plan for a Western States mission in shown in Figures 5 and 6.

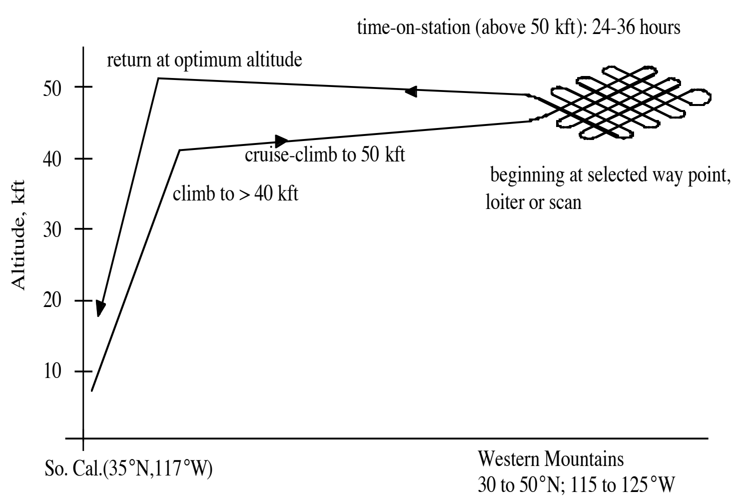

Figure 5. Flight profile for Wildfire Monitoring Mission

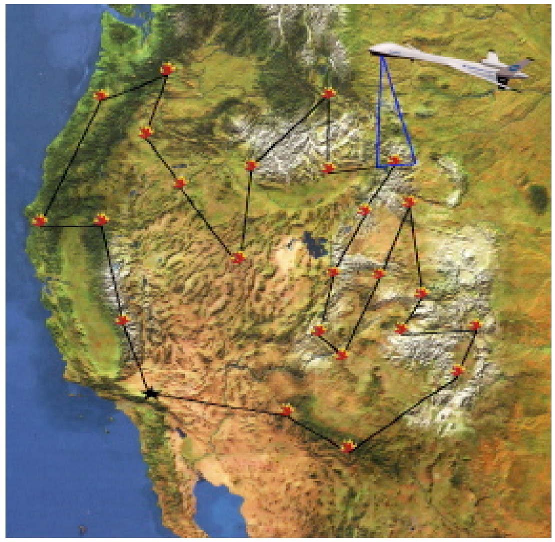

Figure 6. Representative Flight Path for Western States Fire Mission

C. Low-Altitude Fire Perimeters

In addition to high altitude, long endurance (HALE) UAV missions, there are opportunities for low altitude, short endurance (LASE) missions as well. These could be independent missions or coordinated with HALE missions. Fixed or rotary-wing UAVs can be deployed locally to an incident and are highly maneuverable. The major advantage is that they require little or no take-off or landing site preparation. One representative platform is the vertical take-off and landing (VTOL) vehicle, of which there are several autonomous models. Autonomy is a benefit for dynamic route planning. Another opportunity is found in the possibility of coordinating multiple vehicles of different capabilities and operating in different timescales, speeds, altitudes, etc. Some representative missions include:

- Antarctic science, in which a LASE UAV flies short data-gathering flights over land (imagery or environmental measurements) from the deck of a science vessel cruising off-shore.
- Nap-of-the-earth measurements over forests
- Detailed, up-close fire monitoring (described below)

A scenario integrating fixed-wing HALE and rotary-wing LASE vehicle classes in a typical mission would be as follows. The HALE mission proceeds essentially as detailed above. Emerging fire locations are identified and the UAV is tasked to investigate them, as well as monitoring known incidents. As incidents warrant (initially defined and coordinated by ground personnel, but potentially automated – e.g. a fire is growing rapidly in steep terrain, with forecast for dry winds) LASE UAV teams are deployed from the regional fire center or from devolving fires to the incident commander. This deployment could take as long as 12 hours; the HALE UAV would continue to monitor the incident on regular flyovers.

Upon arrival of the LASE UAV, it would be deployed to provide close-in mapping and data from the fire perimeter, starting from the last-known HALE data. Depending on the scale of the LASE UAV, these missions could also include fire suppression activities, delivery of supplies to hand crews, etc. This low-level capability, combined with the asset being dedicated to the local incident, would provide unprecedented real-time knowledge of the fire behavior. Additionally, the all-weather, day-night capabilities of the LASE UAVs, and their ability to operate in difficult terrain, would allow the incident commander to deploy these assets in conditions that are normally proscribed for manned aircraft.

A representative UAV for this type of flight would be the Yamaha RMAX helicopter. A mature aircraft, it has been successfully automated for other surveillance and monitoring missions. This platform and its operation are described in detail in Ref. 6. The perimeter flight is shown schematically in Figure 7.

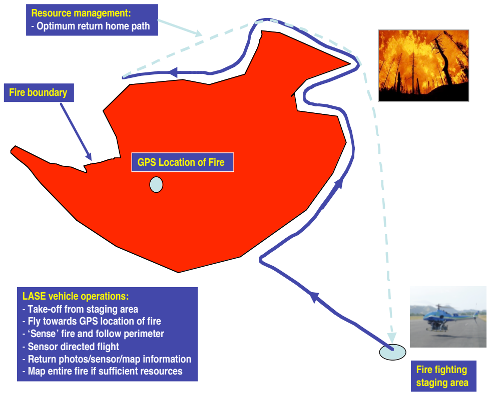

Figure 7. Representative Flight Path for LASE Fire Mission

D. Additional Mission Concepts and Autonomy Needs

Other earth science mission autonomy needs have been derived from the outcomes of a recent NASA workshop on Suborbital Science Missions of the Future.[7] Some representative missions and their Intelligent Mission Management / autonomy requirements are listed in Table 2. Several common features include:

- Following a phenomenon or event in real-time on the basis of in situ sampling measurements or remotely sensed observations or images.
- Controlling multiple vehicles either in formation or in mother-ship / daughter-ship configuration.
- Flying precise geo-coordinate patterns or terrain-following near land or sea-surface.

Table 2. Science Mission Concepts and Autonomy Needs

Science Focus Area	Observation or Measurement	IMM / Autonomy Need
Climate Variability and Change	Solar radiation in a vertical profile	2 or more stacked platforms flying a precise racetrack pattern
Carbon Cycle, Ecosystems and Biogeochemistry	Greenhouse gas (CO_2) flux measurements	Land and sea surface terrain following and air mass tracking
Water and Energy	Cloud properties in a vertical profile	Mothership controlling re-docking or retrievable daughterships
Atmospheric Chemistry and Composition	Tropospheric ozone and pollution tracking	Autonomous retasking of flight direction to follow plumes
Weather	Hurricane cyclogenesis, evolution and landfall	Stacked platforms in autonomous event tracking mode
Earth Surface and Interior Structure	Polar ice sheet dynamics	Coordinate multiple platforms and data streams

V. Current Activities and Plans

Autonomous control of platform and payload on a UAV shows great promise for future science missions. The Intelligent Mission Management / Autonomous Robust Aviation project has had a very successful start, constructing Concept of Operations and Functional Requirements documents, building simulations of the high altitude and low altitude fire missions, designing the information interface and flight controller, and planning a 5-yr program to implement science mission autonomy on UAVs.[8]

A simulation activity has focused on the high altitude fire monitoring mission. The simulation accepts target information from MODIS fire mapper, or other external sources and plans a surveillance path optimized to reach as many of the indicated fires as possible within flight time. The path can be modified during the mission by new information or change in weighting of the targets, on the basis of fire size or local population density, for example. A screen shot from the simulation is shown in Figure 8.

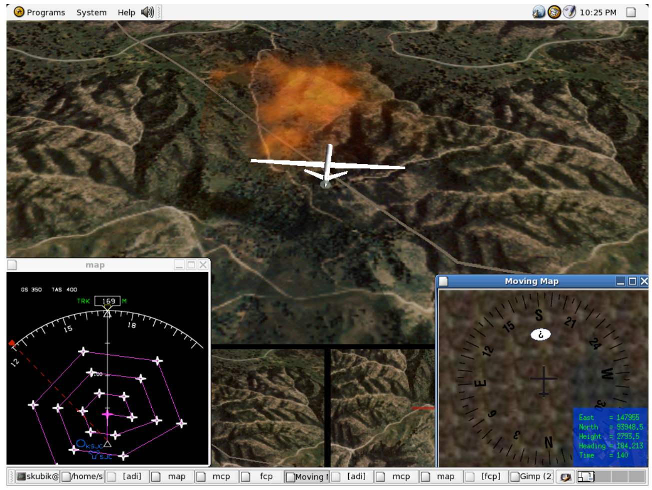

Figure 8. Screen View of Altair High-Altitude Fire Monitoring Mission

The major proposed milestones for the future are:

- Oct 2006 - Demonstrate Mission-Level Decision Aid
  Goal: Demonstration of a collaborative decision environment for single UAV operations. Post flight analysis will determine if the mission was successful.
- July 2007 - Demonstrate Single-Ship Auto Navigation
  Goal: Demonstration of an IMM architecture capable of long endurance, unaided autonomous navigation via payload-directed flight. The flight will include pre-determined navigation to an event and loiter at the event while sending and receiving information.
- September 2008 - Demonstrate Multi-Payload Decision Aids
  Goal: Demonstration of mission-level decision aids for multiple UAV's and payloads. The system will be designed to operate under full autonomy during emergencies.
- July 2009 - Demonstrate Coordinated Operations
  Goal: Demonstration of a coordinated IMM architecture capable of multi-UAV autonomous operation in the presence of dynamic constraints. High-level autonomous control will be required.

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